

## **Equipment in Support for Polarimetric Imaging**

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### **LONG-TERM GOALS**

The wind-driven sea surface is characterized by wind waves with a wide range of spatial and temporal scales. Small waves, with millimeter to centimeter wavelengths, ride on the longer waves and play a crucial role in fundamental interfacial geophysical processes. These include wind stress, air-sea gas exchange, and optical transmission through the surface, microwave backscatter, amongst others. As well, this small-scale roughness underpins many marine remote sensing technologies, such as scatterometry, altimetry and synthetic aperture radar. These satellite sensors are the primary data sources of winds and waves over the planet's oceans. However, current knowledge of the sea surface roughness is incomplete, especially at these shorter scales, which degrades the accuracy of the satellite data products.

To improve both sensor and modeling accuracy for a wide range of air-sea interfacial processes, a more detailed description of the small-scale roughness is needed. As these scales have small amplitudes, but finite steepness, measuring their slope properties is intrinsically well-suited to their characterization.

The intrinsic capability we have demonstrated for polarimetric cameras to remotely sense the local slope field at high spatial and temporal resolutions makes it uniquely ideal for gathering field data on this previously elusive subrange of the sea surface roughness. The results from systematic research utilizing such an instrument will undoubtedly have a broad impact in enhancing scientific knowledge and technological capabilities related to air-sea interaction.

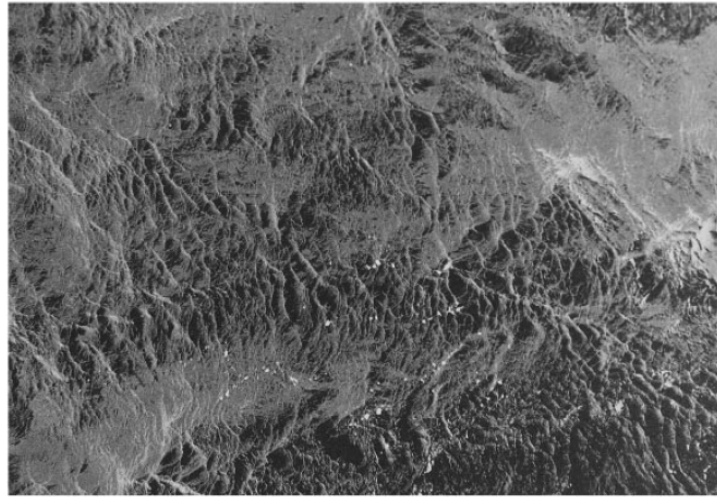
One of the two primary goals of the ONR RaDyO DRI scheduled for FY07-10 is to combine a radiance-based radiative transfer (RT) model with a surface wave model, validate the coupled model with field observations and to investigate the feasibility of inverting the coupled model to yield information on the surface boundary layer.

In this context, air-sea interfacial roughness elements – capillary waves, capillary-gravity waves, short gravity waves, breaking waves as well as their associated foam, subsurface bubbles and spray, contribute substantially to the distortion of the optical transmission through the air-sea interface. Wave breaking signatures range from large whitecaps with their residual passive foam, down to the ubiquitous centimeter scale, microscale breakers that do not entrain air. Figure 1 shows representative small-scale wave features that are typical of the wind-swept sea during active wind wave generation.

Our vision is to develop optical polarimetry as a primary tool for measuring the small-scale sea surface features responsible for the optical distortion processes associated with the air-sea interface. Within our

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proposed innovative complementary data gathering/analysis/modeling effort, we will have a leading



***Figure 1. Image of the fine structure of the sea surface roughness taken during 12 m/sec winds (blowing from top left to lower right) and 3m significant wave height. Field of view is 4m x 2.6m.***

edge capability to provide both spectral and phase-resolved perspectives. These will contribute directly towards our effort within the RaDyO DRI to refine the representation of surface wave distortion in present air-sea interfacial optical transmission models.

## **OBJECTIVES**

At the University of Massachusetts we are developing a new passive optical technique based on polarimetry. Conventional optical remote sensing techniques rely on light amplitude and frequency to carry information about the scattering surface. The polarimetric method exploits these properties, as well as the polarization properties of light to sense information about the scattering media. When the polarimetric properties of light are included, the increased information about the scattering media is striking. We demonstrated in a recent exploratory experiment that the two-dimensional slope field of short gravity wave can be recovered from a distance without interfering with the fluid dynamics of the air or water.

Nondestructive remote sensing methods for measuring the dynamics of ocean surface waves are critical to many important oceanographic and fluid mechanics research topics. Understanding how energy is transferred from the atmosphere to the ocean, the growth and decay of waves, and gas exchange are a few examples of research topics that depend on a good knowledge of the ocean surface dynamics. Investigators have often built instruments that exploit the scattering properties of light to sense the air-sea interface. Some examples of light sensing devices include stereo photography, sun glint photography, specular surface stereo, laser slope gauges, laser profiling, and color table slope gauges. The problem with these methods has been extracting sufficient information from passive measurements and constructing a nondestructive instrument for active devices.

The equipment acquired through this grant will allow the research team to build an operational, field-deployable polarimetric imaging system for recovering the two-dimensional time-varying slope field of

short gravity waves at video frame rates. We anticipate that the systems developed by this grant will spark a new class of instrumentation that will benefit a wide variety of oceanography and fluid mechanics research and educational programs.

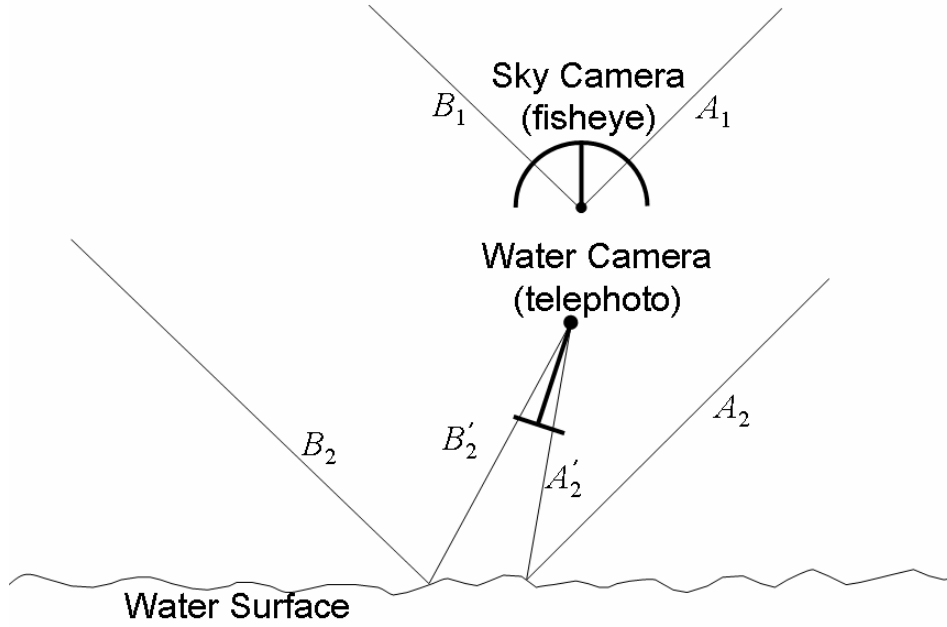
## APPROACH

The Polarimetric Slope Sensing (PSS) concept exploits the scattering properties of light from the air-water boundary to recover the instantaneous two-dimensional slope field of a water surface. Using two cameras, an up-looking wide field-of-view camera that measures the polarimetric properties of the sky radiance, and a down-looking narrow field-of-view camera that measures the polarimetric properties of the reflected sky radiance it is possible to recover the 2-D surface slope of the water surface at every surface facet within the field-of-view of the camera viewing the water surface.

By employing the physics of light scattering from a specular surface, the geometry of surface facets can be found by carefully measuring the polarimetric properties of the source and reflected and/or refracted light. Formally, Stokes proved in the nineteenth century that the polarization state of a bundle of light rays is fully described by the four-component Stokes vector  $\mathbf{S} = (I, Q, U, V)$ . The first component  $I$  measures the intensity of the light. The components  $Q$  and  $U$  measure the degree of linear polarization, and the fourth component  $V$  specifies the degree of circular polarization. This last component is crucial to fully determining the polarization state of a light since, in general, a ray will be elliptically polarized which needs to be decomposed into a linear and a circular polarization vector.

The reflection and refraction of light at a specular surface is described by the Mueller calculus which states the Stokes vectors of the input and scattered rays ( $\mathbf{S}_{\text{in}}$  and  $\mathbf{S}_{\text{out}}$ ) are related by  $\mathbf{S}_{\text{out}} = \mathbf{M}\mathbf{S}_{\text{in}}$ , where  $\mathbf{M}$  is the Mueller matrix. The direction of the rays, the dielectric properties of the air and water, and the Mueller matrix contain all of the information about the scattering (reflection and refraction from the air-water interface). Thus, by measuring the components  $\mathbf{S}_{\text{in}}$  and  $\mathbf{S}_{\text{out}}$  as well as the direction of the source and scattered rays, the orientation of the surface facet can be computed.

At the heart of the system is a polarimetric camera that takes four component images, where the components correspond to the  $I, Q, U, V$  elements of the Stokes vector. A polarimetric camera is similar to a three-component  $R, G, B$  color camera, except that four components instead of three are taken, and the components correspond to the elements of the Stokes vector instead of color.



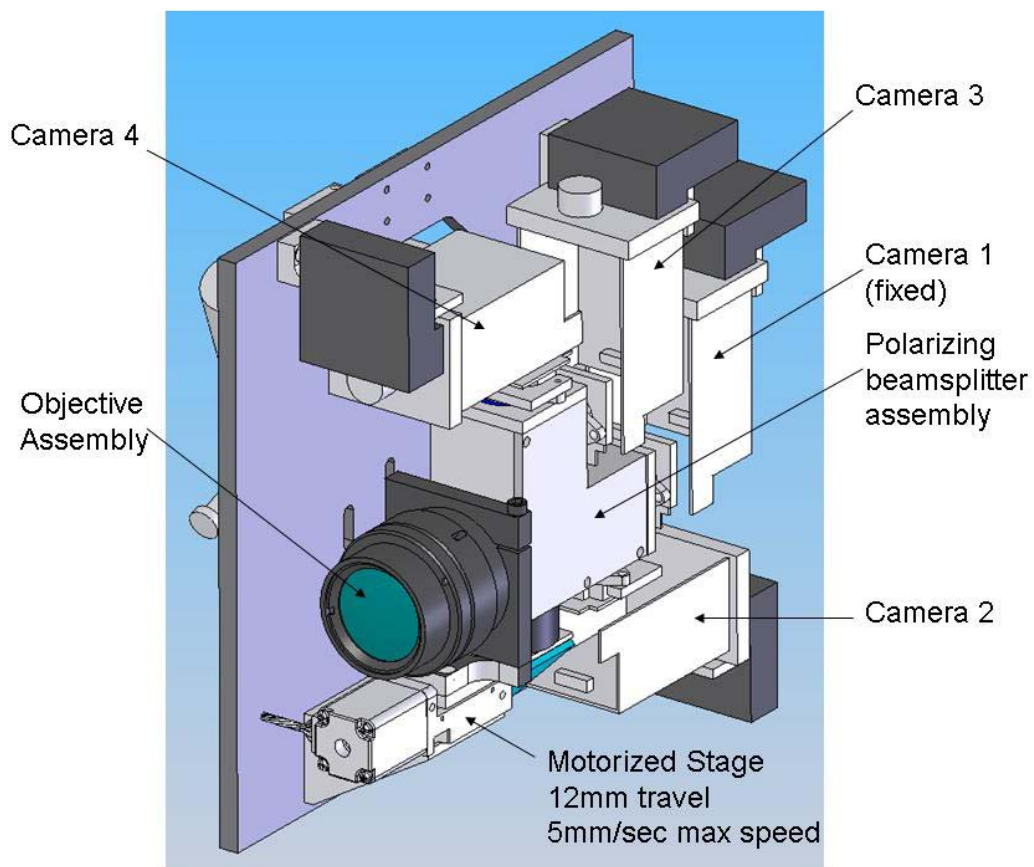
**Figure 2.** *The polarimetric slope sensing concept – The Sky Camera measures the Stokes vector of the source radiance, and the Water Camera measures the Stokes vectors of the source radiance reflected into its field-of-view.*

The experimental setup (depicted in Figure 2) consists of two polarimetric cameras, a Sky Camera that takes wide field-of-view polarimetric images of the sky, and a Water Camera that takes narrow field-of-view polarimetric images of the water. In the Figure, the Stokes vectors of the incident rays  $A_1$  and  $B_1$  are observed by the Sky Camera through a fisheye lens. The incident rays  $A_2$  and  $B_2$  (which are parallel to  $A_1$  and  $B_1$ ) reflect from the water surface and are observed by the Water Camera through a telephoto lens. Under the assumption that the separation between the cameras is small compared to the distance from the cameras to the sky, the rays  $A_1$  and  $A_2$  have the same Stokes vectors. Similarly,  $B_1$  and  $B_2$  have the same Stokes vectors. The Water Camera measure the Stokes vectors of the reflected rays  $A_2'$  and  $B_2'$ . From the physical principles governing the reflection of light from a smooth dielectric surface, the slope of the surface can be found from analyzing the Stokes vectors of the incident and reflected rays. Thus, the water surface slope where the ray  $A_2$  reflects from the water surface is found by analyzing the measured Stokes vectors of  $A_1$  and  $A_2'$ . Similarly, surface slopes can be computed for all reflected rays imaged by the Water Camera.

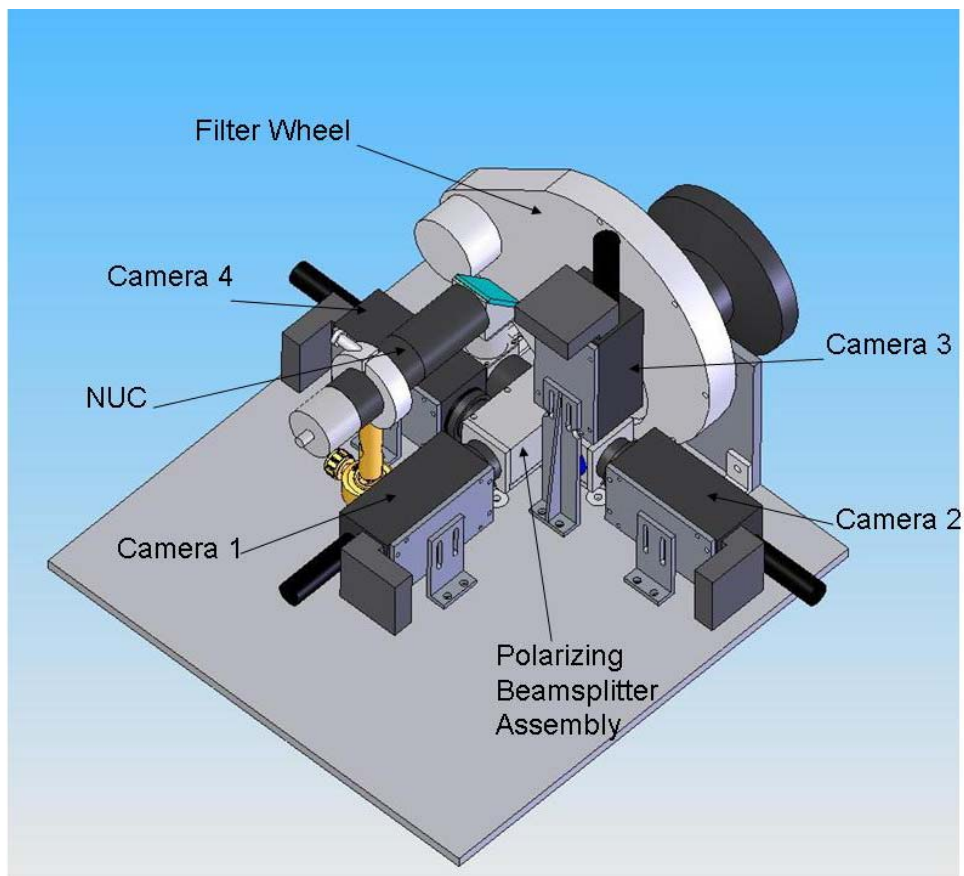
## WORK COMPLETED

We completed a preliminary design for the sky and water polarimetric cameras. Figures 3 and 4 show the computer aided design (CAD) drawing for the cameras. The narrow field-of-view imaging polarimeter (N-IPol) uses a custom telephoto objective lens with a  $3^\circ$  field-of-view and the wide field-of-view imaging polarimeter (W-IPol) uses a combination of custom optics and an off-the-shelf fish eye converter and incorporates an 8-position color wheel. The N-IPol was delivered in December 2007 and the W-IPol was delivered in February 2008. The N-IPol was tested at the Scripps Institute of

Oceanography (SIO) Pier Experiment January 6-28, 2008, and is currently deployed in the RaDyO Benign Conditions Experiment in the Santa Barbara Channel.



*Figure 3. CAD drawing of the imaging polarimeter that looks at the water surface.*



*Figure 4. CAD drawing of the imaging polarimeter that looks up at the sky.*

A wave tank facility was built to test the Polarimetric Slope Sensing techniques in laboratory conditions. The wave tank facility consists of an 72" x 35" x 12" tank made form aluminum frame and glass panels, a paddle wave maker, and flat panel monitor attached to the bottom glass and a 3-CCD color camera.

## RESULTS

In collaboration with Dr. Andres Corrada-Emmanuel, Dr. Christopher Zappa and Professor Michael Banner we completed the analysis of a proof-of-concept study<sup>1</sup> to assess the effectiveness of a new passive optical technique based on polarimetry. The Polarimetric Slope Sensing (PSS) concept exploits the scattering properties of light from the air-water boundary to recover the instantaneous two-dimensional slope field of a water surface. In principle, the polarization vector properties [polarization orientation and degree of linear polarization] of the sea surface reflection of incident skylight provide sufficient information to determine the local surface slope vector normal relative to the camera orientation. A controlled laboratory tank experiment was carried out with mechanically-generated gravity waves at Lamont-Doherty Earth Observatory. The second phase of this study was performed from the Piermont pier on the Hudson River, near Lamont Doherty Earth Observatory. The results

<sup>1</sup> PI: Chris Zappa, Title "Ocean Surface Wave Optical Roughness: Innovative Polarization Measurement" ONR award number: N00014-06-1-0372.

were published in Measurement Science and Technology (Zappa, Banner, Schultz, et al 2008). In addition, the imaging polarimeter design was presented by Dr. Larry Pezzaniti, with Polaris Sensor Technologies at the SPIE Defense and Security (Pezzaniti et al, 2008), and Dr. Howard Schultz presented the Polarimetric Slope Sensing method at the Ocean Sciences Meeting (Schultz et al, 2008).

We were able to draw several conclusions about the instrument requirements for future studies. A complete test of the concept would require two polarimetric cameras – one that measures the incoming sky radiance, the other that measures the reflected (or refracted) radiance. The camera should have a dynamic range capable of imaging in non-uniformly illuminated sky conditions. It would be desirable for the polarimetric cameras to be able to measure the complete four-component Stokes vector. In realistic field conditions, sky radiance is often partially polarized. Furthermore, reflection of linear polarized skylight adds a small, but measurable circular polarized component. The surface-viewing camera should have an integration time fast enough to freeze the motion of short gravity wave riding on ocean swell, and a frame rate fast enough to capture their temporal structure.

## **IMPACT/APPLICATIONS**

Emerging optical remote sensing techniques based on polarimetry have the potential to provide high spatial and temporal resolution topographic information about ocean surface waves. Our recent work within this DURIP award “Equipment in Support for Polarimetric Imaging” (N00014-07-1-0731) and the ONR RaDyO DRI has developed an imaging polarimeter that successfully recovers two-dimensional slope fields at up to 60 Hz frame rates of very short gravity wind waves down to capillary waves.

When applied to oceanography and fluid mechanics problems, polarimetric imaging techniques have the potential of significantly improving the ability of investigators to study surface overturning and bubble production associated with open ocean wave breaking are the major drivers of upper ocean turbulence production and mixing, and dissipation of wave energy. In addition, breaking waves generate sea spray and droplets, and enhance microwave backscatter and underwater ambient noise generation.

In principle the Polarimetric Slope Sensing technique can be applied from vantage points above and below the water surface. In the RaDyO program the focus is on using a down looking imaging polarimeter. However, several unique applications exist for deploying a submerged, up looking, imaging polarimeter. An important facet of our long term goals is to determine the feasibility of using a submerged imaging polarimeter to recover the surface slope field. The advantages to observing the surface from below includes, reduced interference of the surface wind and wave field from the observation platform, and an increase in the amount of light energy reaching the sensor.

A submerged, up looking polarimeter, may enable imaging the surface environment from a subsurface sensor. This application is based on four-step process for removing image distortion caused by surface waves (see PATENTS below). The first step employs an imaging polarimeter to measure the polarimetric radiance of down-welling light from a vantage point below the water surface. The system then computes the 2-dimensional surface slope field from the polarization change caused by light refracting through the water surface. In the third step, Snell’s law is used to compute the change in orientation of the refracted light rays. Finally, the system uses the change in orientation to remove the image distortion cause by light refracting through the wavy air/water interface. After applying this



process, the resulting images have the appearance of being taken through a flat water surface. We therefore refer to this process as optical flattening.

The optical environment associated with observing transmitted light is significantly different from observing reflected light. The methods developed for observing reflected light cannot be directly applied to an up looking configuration. Consequently, additional studies are needed to extend the Polarimetric Slope Sensing technique to an up looking configuration.

## **RELATED PROJECTS**

The imaging polarimeters are part of a multi-institutional ONR research project-Radiance in a Dynamic Ocean (RaDyO) program. The primary research goals of the program are to (1) examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes; (2) construct a radiance-based SBL model; (3) validate the model with field observations; and (4) investigate the feasibility of inverting the model to yield SBL conditions. The goals of our team are to contribute innovative measurements, analyses and models of the sea surface roughness at length scales as small as a millimeter. This characterization includes microscale and whitecap breaking waves.

## **PUBLICATIONS**

Howard Schultz, Chris J. Zappa, Michael L. Banner, Andres Corrada-Emmanuel and Larry Pezzaniti (2008) "A Method for Recovering the Two-dimensional slope field of the Ocean Surface Waves Using an Imaging Polarimeter," 2008 Ocean Sciences Meeting, Orlando, FL March 2-7, oral presentation. [Published, Referred]

J. Larry Pezzaniti, David Chenault, Mike Roche, John Reinhart, Joseph P. Pezzaniti, and Howard Schultz (2008) "Four Camera Complete Stokes Imaging Polarimeter," SPIE Paper # 6972-19 Polarization: Measurement, Analysis, and Remote Sensing VIII, SPIE Defense and Security, Orlando, FL March 17-20. [Published, Referred]

Christopher J. Zappa, Michael L. Banner, Howard Schultz, Andres Corrada-Emmanuel, Lawrence B. Wolff & Jacob Yalcin (2008) "Retrieval of short ocean wave slope using polarimetric imaging," Measurement Science and Technology, 19, 055503, doi: 10.1088/0957-0233/19/5/055503. [Published, Referred]

## **PATENTS**

Howard Schultz and Andres Corrada-Emmanuel, "System and Method for Imaging Through an Irregular Water Surface," filed with the USPTO by the University of Massachusetts, 2006, 2007.